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Materials Systems Inc.

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**COST-EFFECTIVE METHOD FOR SYNTHESIZING
INNOVATIVE TRANSDUCER MATERIALS FOR
SENSORS AND ACTUATORS**

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COST-EFFECTIVE METHOD FOR SYNTHESIZING INNOVATIVE TRANSDUCER MATERIALS FOR SENSORS AND ACTUATORS

Executive Summary

Piezoelectric ceramic/polymer composites have many applications in advanced Navy tranducers and commercial ultrasonic imaging. Unfortunately, their application has been limited by the lack of a manufacturing-viable technology capable of meeting both the low cost and high volume production requirements. The principal manufacturing difficulty lies in the handling of millions of fine PZT rods during their assembly into a typical composite transducer.

In prior ONR-funded research, Materials Systems Inc. (MSI) has demonstrated that ceramic injection molding is capable of meeting the stringent transducer cost and assembly needs of piezoelectric ceramic/polymer composites for Navy applications. The injection molding approach overcomes the difficulty of assembling oriented ceramic rods into composite transducers by net-shape preforming ceramic rod arrays. The process also makes feasible the construction of composite transducers having more complex element geometries than those previously envisioned, leading to greater design flexibility for improved acoustic impedance matching, lateral mode cancellation, and superior actuator performance.

Tooling constitutes the largest single cost factor in manufacturing piezoelectric ceramic/polymer composites by injection molding. The cost of tooling is normally recovered over the tool life by fabricating millions of parts, at a very low per part tooling cost. For prototype development and short production runs, tool cost is a significant factor in the part price and can inhibit the demonstration of new composite designs.

In this work, MSI has developed a new type of tooling that simultaneously reduces both tool cost and fabrication lead time. By using low cost, soft materials, the tool inserts become more easily formable. The trade-off is reduced tool life, but this is usually not important in short run manufacturing and prototype development. Using this approach, MSI has demonstrated the ability to fabricate a 1-3 tool configuration having over 3000 individual PZT rod cavities

as small as 0.5mm in diameter. The tool cost for this configuration, after subtracting out engineering costs, is approximately \$3000, compared with vendor-quoted costs of \$100,000 to \$150,000 for the same tooling made using MSI's existing high-durability hard steel tool technology. MSI has shown the new tooling approach to be suitable for fabricating complex 1-3 PZT element geometries that can not be formed by the conventional dice-and-fill method. Such a complex element geometry tool has been purchased under the Phase 1 program and is currently under evaluation.

Phase I Technical Objectives and Deliverables

The overall objective is to design, demonstrate, and implement a cost-effective tooling technology for manufacturing piezoelectric composite materials by injection molding. This requires a new tooling approach which complements the existing MSI low cost PZT ceramics injection molding technology, currently used in 1-3 piezocomposite research and manufacturing.

This objective has been approached by first selecting composite configurations of current interest to ONR as a testbed for the new tooling technology. Tooling design and fabrication then became the major focus of effort throughout Phase 1. Finally, the feasibility of using the tooling to mold a 1-3 composite array was evaluated in preparation for tooling refinement and application in Phases 2 and 3. The program plan for Phase 1 is as shown in Figure 1.

The primary Phase 1 research deliverable emphasizes establishing the tool insert fabrication technology and designing and debugging the assembled injection molding tool. This report, the final Phase 1 contractual deliverable, documents the research results and makes recommendations for tooling technology refinement and composite fabrication and evaluation in Phase 2, and composite transducer application in Phase 3.

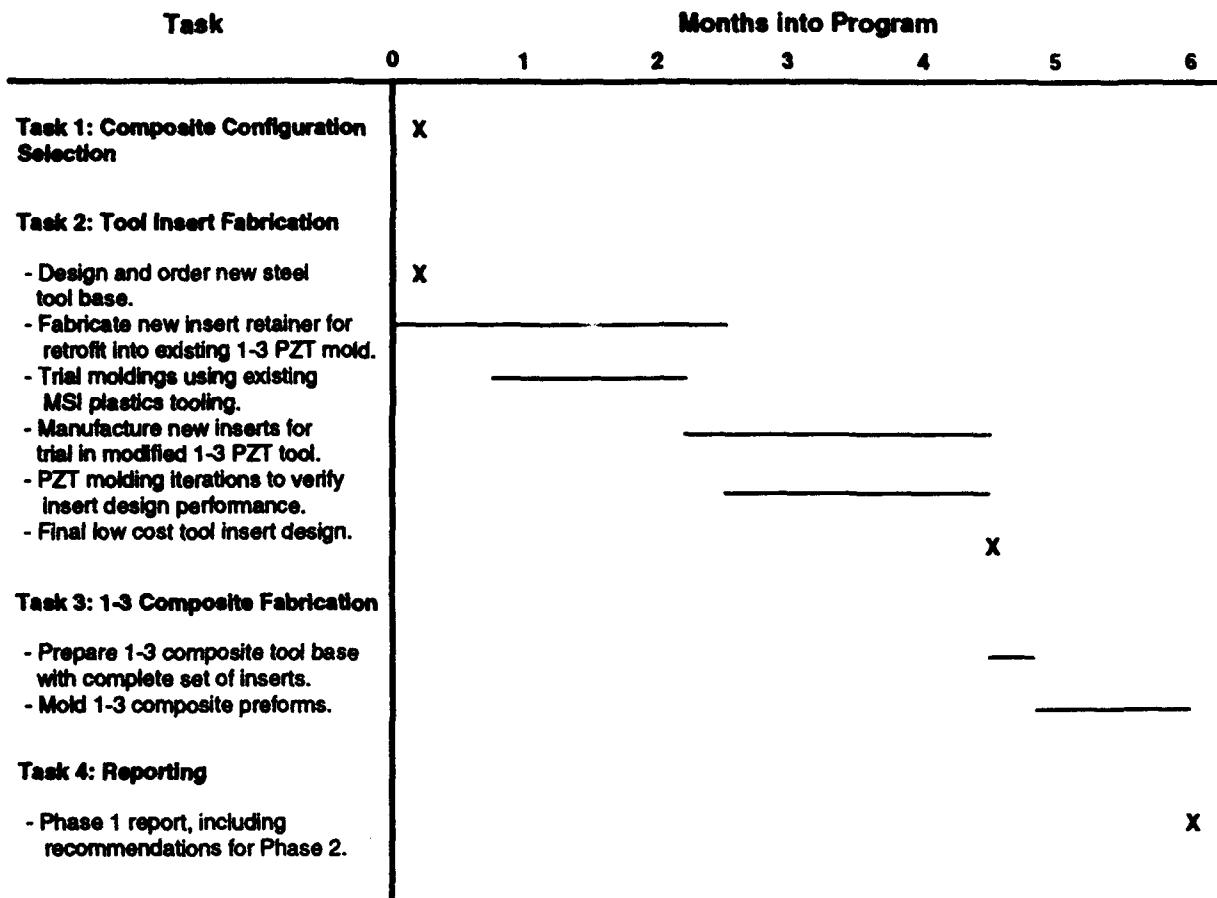


Figure 1. Phase 1 Program Plan

2. Accomplishments versus Objectives

All of the planned objectives were met on schedule and within budget. The basic feasibility of injection molding PZT with the new tool inserts has been established using the current MSI injection molding process. With one set of tool inserts, having approximately 3000 PZT rod cavities over a 50mm square area, complete tool filling was obtained under only modest injection pressure. The tool withstood the required injection pressure over multiple molding cycles.

An additional 1-3 composite design has been established to test the capabilities of the new tooling approach for fabricating configurations that are not feasible with conventional dice-and-fill technology. These are interesting because of the potential for improving the composite performance in resonant applications by deliberately configuring the PZT element shape and layout to cancel spurious responses. Tool inserts with the new configuration have been ordered and are being evaluated during the completion of the Phase 1 effort.

3. Technical Approach

Figure 2 shows the classical 1-3 piezocomposite configuration, consisting of an array of PZT ceramic rods arranged in a piezoelectrically-inert polymer matrix (1, 2). The difficulty of manufacturing such composites has previously been lack of a cost-effective technology for forming and handling millions of PZT rods during composite assembly. This difficulty has been resolved by using net-shape forming to fabricate the PZT elements as a single-piece array instead of as individual rods (3). Such an array is illustrated in Figure 3. In this configuration, the alignment and spacing of the PZT rods is maintained using an integral PZT base plate. The MSI technical approach uses injection molding to fabricate such PZT preforms prior to assembly into composites.

Under ONR Contracts N00014-92-C-0010 and N00014-C-93-0104, MSI established the basic injection molding technology required to form PZT into complex shapes suitable for 1-3 composites. This injection molding process is shown schematically in Figure 4. Injection molding is widely used in the plastics industry as a means for rapid mass production of complex shapes at low cost. By injecting a hot thermoplastic mixture of ceramic powder and wax-based binder into a cooled mold, complex ceramic shapes can be formed with the ease and rapidity normally associated with plastics molding. The binder must be removed nondestructively, necessitating high solids loading and careful control of the binder removal process and fixturing. Once the binder is removed, the subsequent firing and poling processes are similar to those used for conventional PZT ceramics.

Under these programs, it has been demonstrated that, with steel tooling, the process is capable of forming composites having PZT ceramic rods of aspect ratio as high as 18 for diameters as low as 0.5mm. Thirty 250mm by 250mm 1-3 composite transducers have recently been completed and delivered under the manufacturing demonstration program.

In a separate ongoing effort (Contract N00014-92-C-0212), MSI is performing basic research aimed at establishing a process for fabricating ultrafine 1-3 composites having fiber diameters in the 200-100 μ m range, with a goal of reaching fibers down to 25 μ m diameter. The applications range from medical ultrasound through nondestructive evaluation to high frequency undersea acoustic

imaging for mine detection. MSI has demonstrated the basic approach for tooling to form these ultrafine PZT structures and has shown that the injection molding process is adaptable for this purpose. This approach is excellent for relatively simple geometry, ultrafine scale composites for use at megahertz frequencies.

The current Phase 1 technical approach draws upon experience gained in all of the above programs to provide the capability for fabricating piezoelectric ceramic/polymer composites in the important 0.3 to 1mm diameter size range and with more complex configurations than those covered by the existing research. The frequency ranges that are expected to become available are of great interest for mine detection, acoustic noise suppression, and underwater sensing.

The tooling approach draws upon designs previously developed and reported elsewhere (4), and involves using specially configured tool inserts fitted into a standard injection molding tool base. This configuration is shown schematically in Figure 5. The tool inserts are designed so that the molded 1-3 PZT rod array is integrated onto a PZT base that acts as a carrier for use in composite assembly. The key to reducing tool cost lies in replacing the existing hard steel tool inserts with inserts made from softer materials that can readily be formed into the desired shape. This makes possible many new PZT rod configurations that cannot be fabricated using existing processes. For example, features such as acoustic impedance matching and lateral mode cancellation can be accomplished simply by adjusting the PZT element geometry and layout. Some examples of candidate PZT 1-3 element arrays are shown in Figure 6. Such devices are made possible by net-shape PZT ceramic injection molding.

The technical approach has addressed tooling design, fabrication, and demonstration in three distinct tasks. In Task 1, Composite Configuration Selection, MSI has consulted with ONR and NRL-USRD to select a baseline composite for use in designing and debugging the mold fabrication process. Ultimately, this is expected to result in 1-3 composite materials suitable for direct application in undersea imaging, side scan sonar, and commercial undersea sensing. In addition, a separate 1-3 composite design has been selected to demonstrate the capability of the new tooling approach for fabricating complex PZT element layouts, in preparation for broader technology application in medical ultrasound, NDE, and advanced undersea acoustic imaging and sensing.

In Task 2, Tool Insert Fabrication, MSI has demonstrated an approach for fabricating tool inserts that retrofit into the current steel tool base, modified to operate with soft, readily-formed insert materials. The insert fabrication procedure has been established, and several generations of inserts have been made and tested in the modified tool base. Full tool operation has been demonstrated in the molding equipment, followed by actual molding trials using the existing MSI PZT injection molding materials and procedures.

For Task 3, 1-3 Composite Fabrication, the approach has been to assemble finished inserts into a new, specially-fabricated steel tool base large enough to form a 1-3 PZT element array up to 50mm square after sintering. This array has been tested by running the full set of inserts under representative injection molding conditions to establish mold filling behavior and ejection requirements.

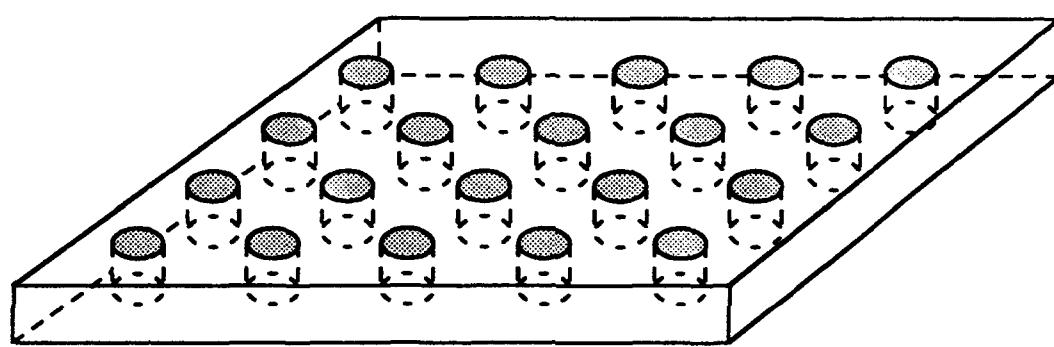


Figure 2. 1-3 piezocomposite with individual rods of PZT ceramic in polymeric matrix.

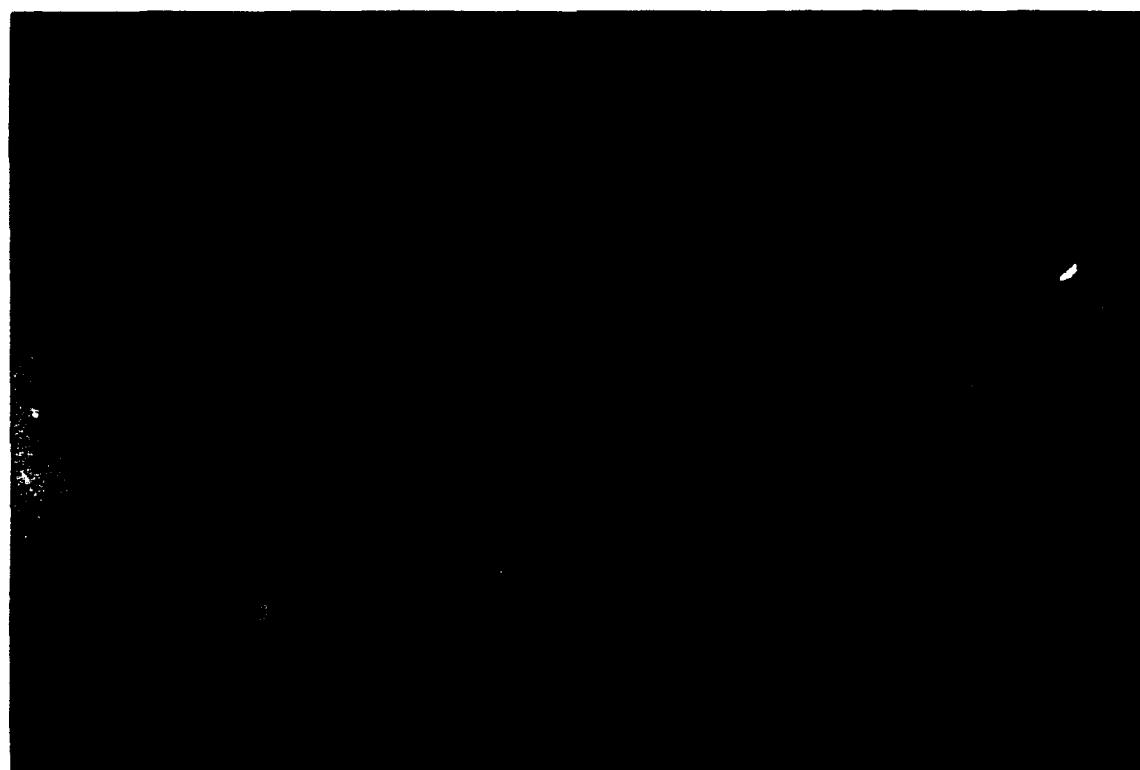


Figure 3: Current MSI SonoPanel injection molded PZT preform.

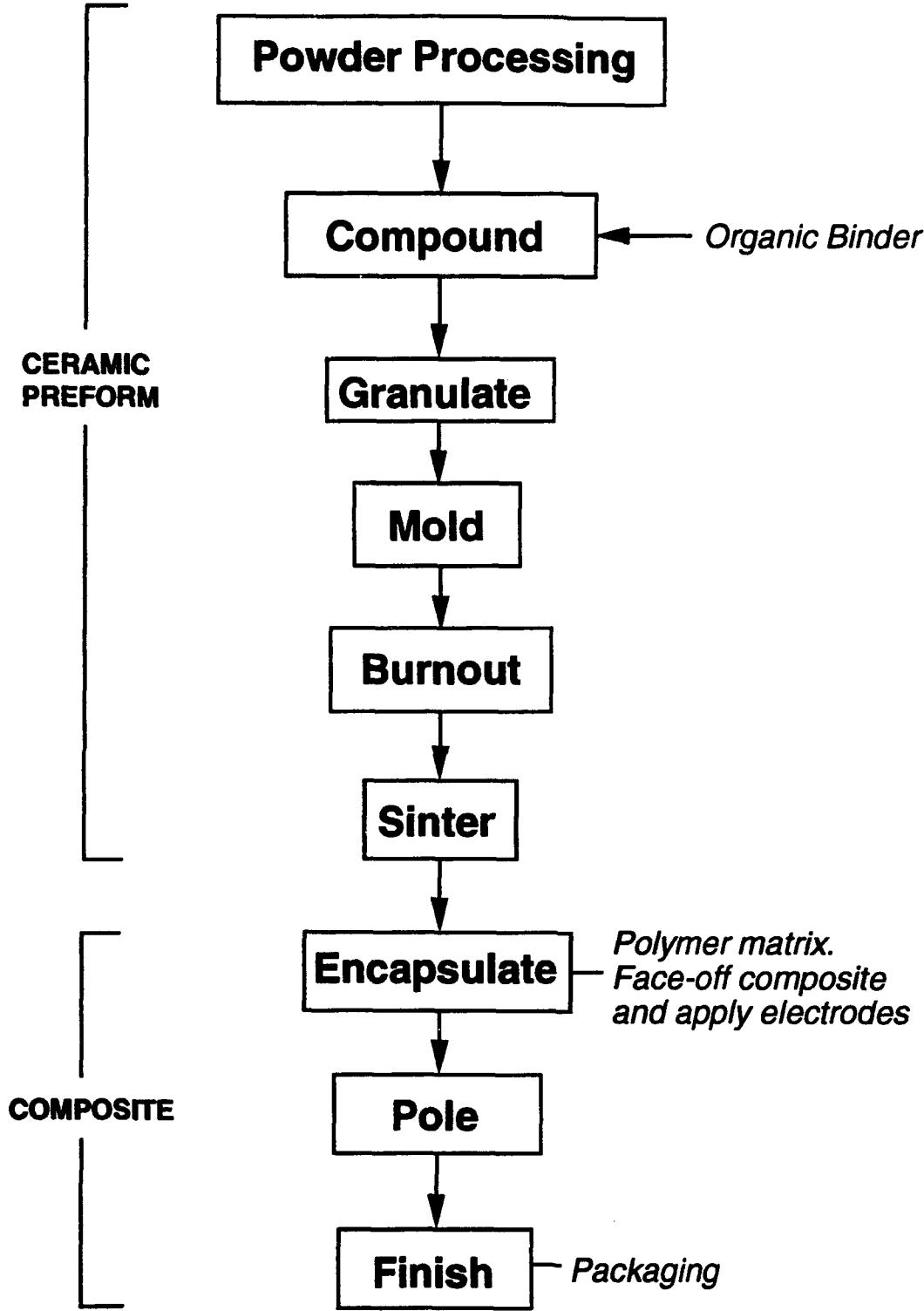
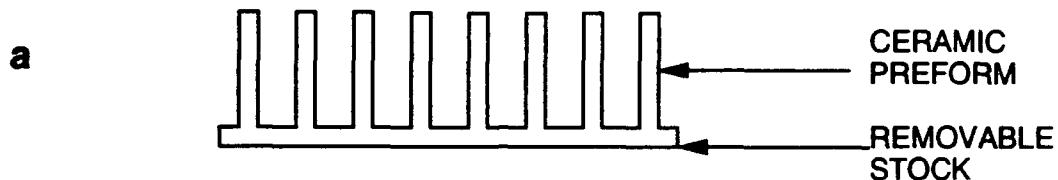
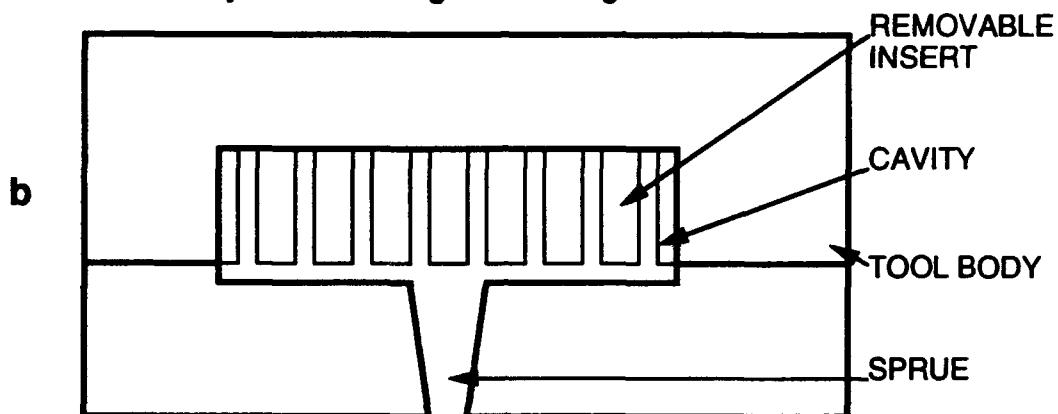


Figure 4: Injection molding process flow for fabrication of 1-3 composite transducers.

Preform Configuration (500-10,000 ceramic elements)



Injection Molding Tool Configuration



Tool Insert Design Permits Composite Design Flexibility



Large Area Composite Arrays made from Preforms

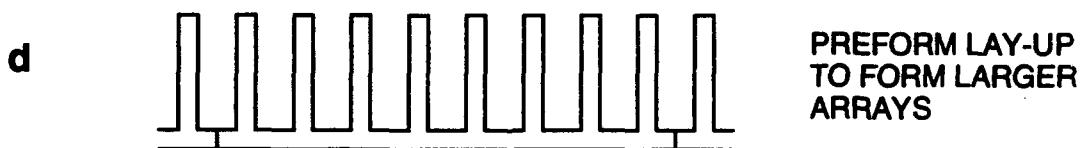


Figure 5: Composite fabrication approach using injection molded PZT preforms. Figures 5a and 5b illustrate the tooling used to mold a typical PZT ceramic preform. In this approach, shaped tool inserts form the PZT elements. Examples of alternative design configurations are shown in Figure 5c, illustrating possible variations in PZT element geometry and spacing. Figure 5d shows how individual preforms are configured to form larger arrays.

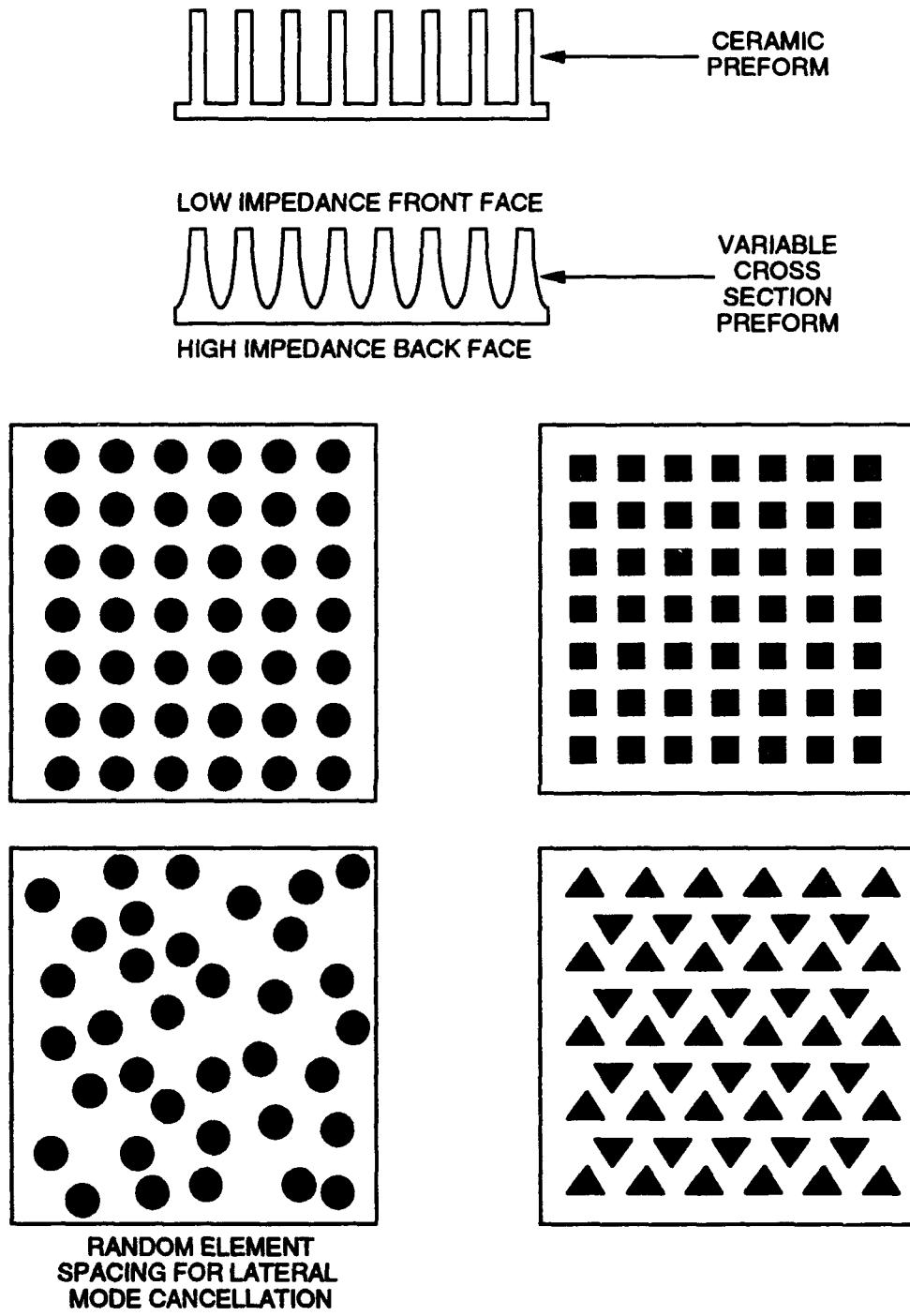
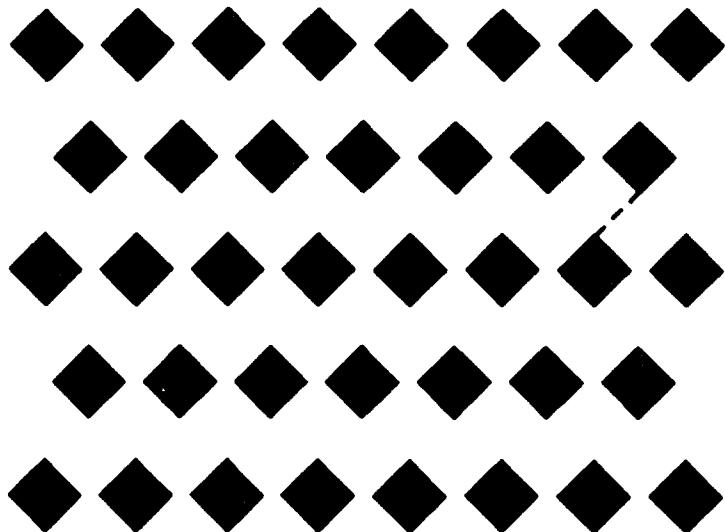
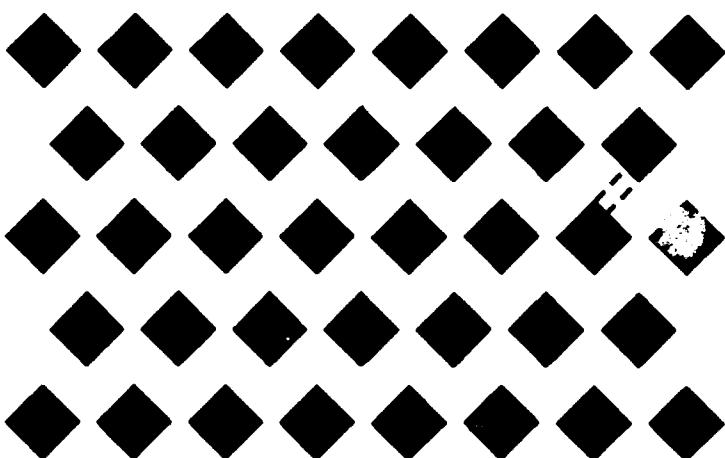


Figure 6: New concepts for improved 1-3 piezocomposites, showing variations in PZT element shape and layout which can be incorporated through net shape fabrication to enhance specific transducer performance characteristics.

25.4 vol percent PZT



32.6 vol percent PZT



36.9 vol percent PZT

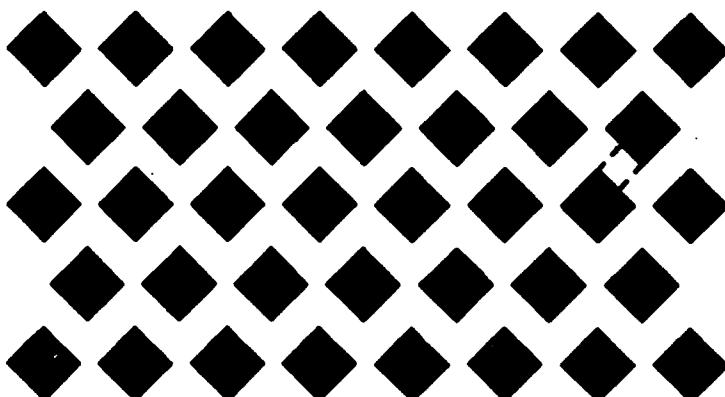


Figure 7: New 1-3 composite design utilizing square cross-section PZT elements arranged so as to minimize adjacent surface overlap. This configuration can not be made by conventional dice-and-fill approaches.

4. Results

For convenience of presentation, the results of this program are described under the task format assigned in the original program plan (Figure 1).

Task 1: Composite Configuration Selection

After consultations with the ONR contract monitor and the staff of NRL-USRD, a first generation 1-3 composite configuration was selected as the testbed for low cost tooling development. The configuration chosen contains 25 volume percent of 0.5mm diameter by 5mm long cylindrical PZT rods on a 50mm square PZT base. 1-3 composites made from this material would be expected to be capable of resonant operation in the frequency range 0.4-1.5MHz. NRL-USRD has already tested composites with similar dimensions made by the conventional dicing technique.

This configuration represents an extremely difficult challenge in terms of PZT element density. Such an array contains over 3000 PZT elements within a 50mm square area. The decision was made to fabricate this full set of PZT elements, rather than a scaled-down version, to allow the new tool base to be mated directly to existing tooling and eliminate the need for duplicating the existing hot sprue assembly. This saves set-up time during tool changes as well as tool base cost.

In addition, a new composite configuration having square cross-section PZT elements has been designed and is being evaluated as part of Phase 1. Figure 7 shows several versions of this insert geometry in which the PZT volume fraction ranges from 0.25 to 0.37. One advantage of this geometry is the ease with which the overlap of adjacent PZT element faces can be varied. Thus, the PZT rods are oriented so as to minimize face-to-face contact area, with the intention of reducing interelement cross-talk. Note that this design is not fabricable by the dice-and-fill method. This design makes feasible, for the first time, controlled experimental variation of the interelement acoustic coupling, which is one possible route for enhancing transducer performance. Another advantage lies in the ease with which this element configuration can be tapered. Element taper has been studied in the prior ONR work and found to be an

important factor in successfully controlling the ejection of the molded array from the tool.

Task 2: Tool Insert Design and Fabrication

A new tool base has been designed and built to replace the moving half of the current coarse-scale 1-3 composite tool. By this means, the cost of duplicating the stationary portion of the tooling was avoided, and the current coarse-scale 1-3 tool was retained intact so that production for other contracts and commercial applications was not interrupted. The new tool base was equipped with a similar ejection mechanism to that used in the existing conventional tool (4).

In the new tool, the insert array is driven hydraulically by the injection molder through a pair of hardened steel dowels attached to the tool ejector plate. A steel retainer frame positions and properly spaces the inserts. This design has many advantages in terms of simplicity, versatility, and low cost, but has required considerable redesign and modification as a result of molding trials. In particular, the steel dowels proved to be insufficiently stiff and bent under the injection pressure during one molding cycle. Interestingly, the mold inserts survived this pressure undamaged, but had to be replaced with new inserts modified to accept thicker dowels. Aside from this single difficulty with the ejector mechanism, the tool base design has proved itself through several iterations of insert development and many trial moldings. Minor design improvements are needed in the insert locating and tensioning mechanisms, but the basic function of the tool base has been demonstrated for Phase 1 purposes.

Several iterations of tool inserts have been fabricated using the materials and procedures identified in the original proposal. Fabricating these inserts has required some process development, as well as redesign of the overall configuration. Insert fabrication, which is the most important part of the tool cost savings approach, now appears straightforward.

The principal challenges anticipated at the commencement of the Phase 1 effort in terms of low cost tool inserts were:

1. Tool insert material properties, especially stiffness, wear and thermal

conductivity.

2. Tool insert fabrication tolerances, which are extremely tight because of the need to avoid the tolerance stacking that leads to tool flashing during molding.

Tool insert properties proved to have little impact on moldability. The thermal conductivity is adequate for molding at the rate of about one part per minute, the current rate used in 1-3 composite molding using semiautomatic operation and existing tooling. The tool inserts have been operated many times over the course of the program, with very little evidence of wear. Indeed, the original estimate of the tool life, approximately one hundred moldings, may be revised upward based on results to date. With proper insert positioning, the array of inserts becomes self supporting, and insert stiffness does not pose a problem.

Tool insert dimensional tolerances have proved to be much more critical. The injection molding operation imposes severe stresses on all portions of the tool cavity since molding pressures are typically in the 7 to 100MPa range. Aside from the obvious physical damage that can occur if the tool is structurally weak, such as in the dowel area referred to above, the pressure of the molten ceramic/binder mixture and the impact of the flow during initial injection can force open gaps between the inserts and lead to flashing. This has been the most difficult technical problem to date, and has only recently been resolved.

For the first molding trials, the machine parameters were the same as those used with the conventional hard steel tool. Under these conditions, the injection pressure proved too high and severe tool flashing occurred. Upon dismantling and inspection, the tool inserts were found to vary in thickness by 10 μ m. This alone is insufficient to cause flashing, but when these tolerances stack up over a 58 by 58 array of inserts, a gap as wide as 600 μ m can result, easily capable of allowing the liquid molding mixture to escape and preventing the pressure build-up needed for successful mold filling. Flashing was also found to distort the tool inserts sufficiently that the frozen PZT/binder mixture caused the ejection mechanism to bind, requiring dismantling and reassembly of the tool.

Accordingly, the tool inserts were returned to the toolmaker for surface machining to adjust for the $10\mu\text{m}$ insert dimensional variation. The remachined inserts were reassembled in the tool base, and molding trials resumed at lower pressures. With this correction, the flashing problem was largely eliminated. Full molding pressure was achieved and the tool cavities properly filled during molding.

Unfortunately, although accurately remachining the inserts corrected the flashing problem, this operation would add significant cost to the tool. Accordingly, attempts were made to incorporate a correction into the insert fabrication procedure to adjust for the $10\mu\text{m}$ insert dimensional variation. This proved successful in terms of dimensional control, but led to an uneven insert surface that interfered with the ejection function. As the last step in tooling refinement, a lapping procedure has been developed that produces an excellent surface finish on the inserts without adding significantly to the tool cost. This approach has been adopted for assembly of the subsequent tooling iterations and appears to be a viable long term solution to the need for accurate insert dimensional tolerances.

Task 3: 1-3 Composite Fabrication

Once the tool design and fabrication issues were identified and resolved, 1-3 composite injection molding has proved to be relatively straightforward. Mold filling has been accomplished using lower pressures than are normally required for 1-3 preform molding. This is presumably because the low rate of heat transfer allows more time for the melt to fill the tool cavities. Care has had to be taken to prevent premature freezing of the PZT base plate. When this happens the result is a partially-filled "short shot." Figure 8 shows an array of 0.5mm diameter round PZT rods molded using the tool iteration made with surface ground inserts. The results of minor flashing are evident due to tool insert distortion during molding. In this case, the result of flashing between individual cavities is a "PZT web" partially bridging the individual rods. Lapping the inserts has tightened up the tool tolerances and largely corrected this effect.

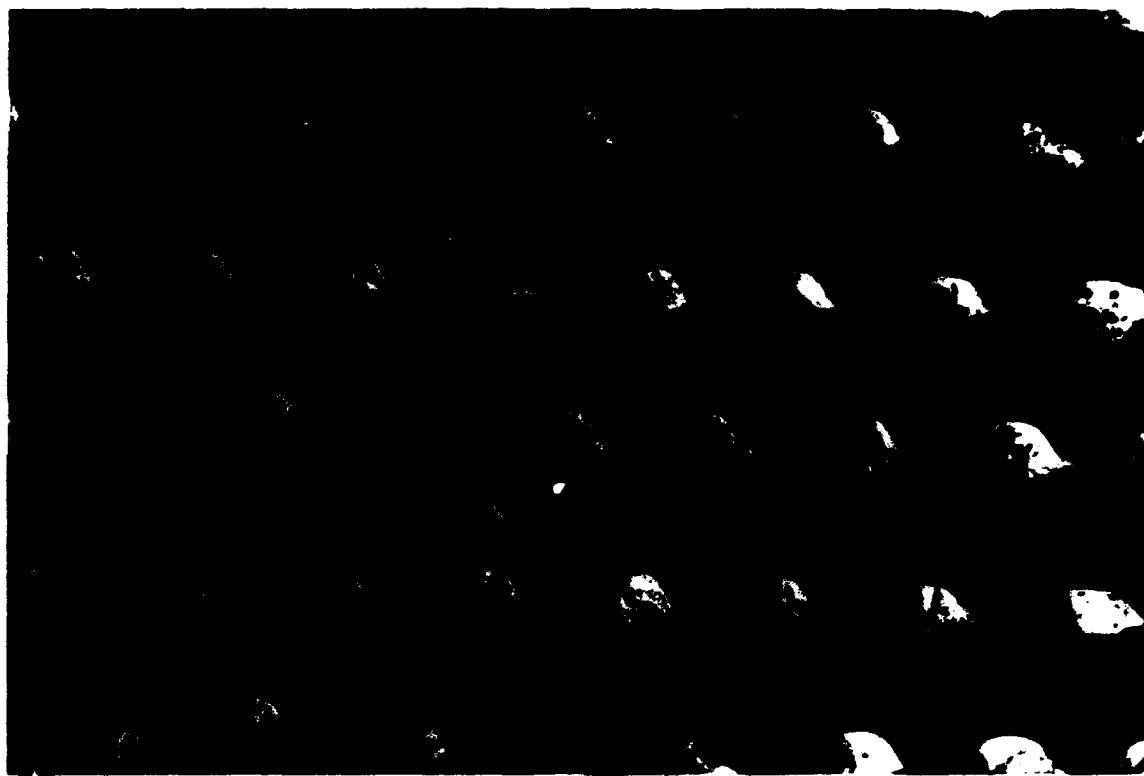


Figure 8: Injection molded 0.5mm diameter rods made using the new tool.

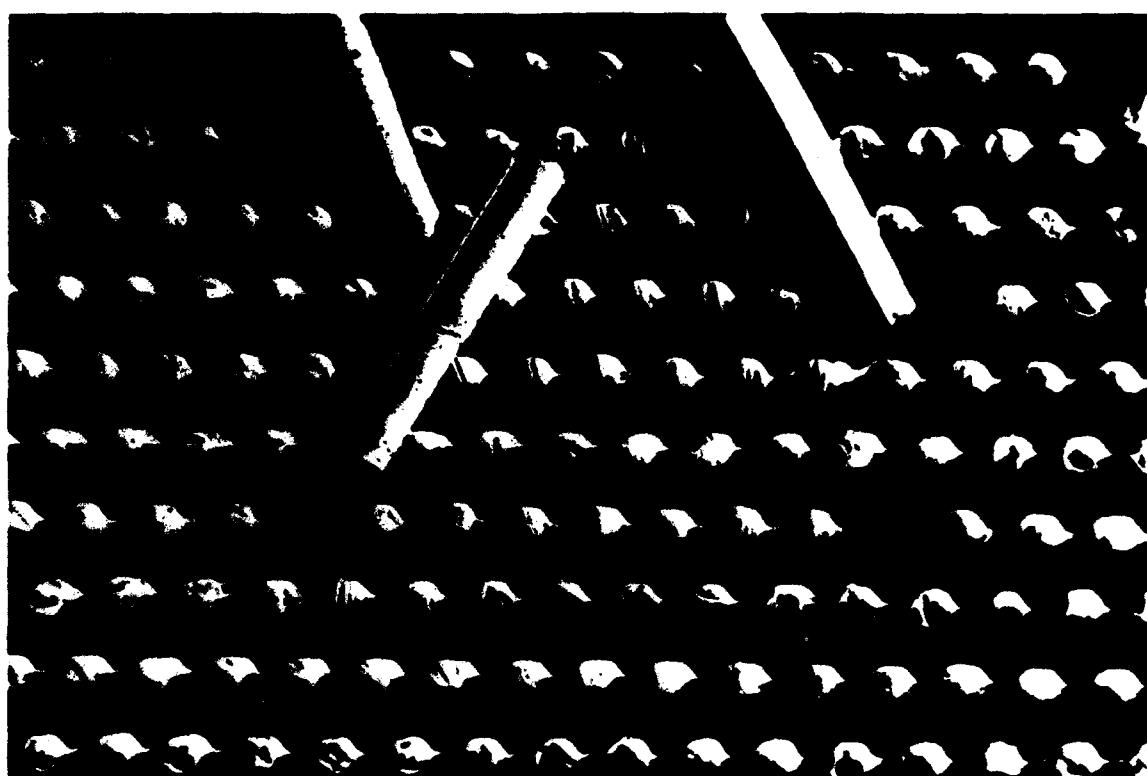


Figure 9: PZT rod array showing the rod aspect ratio.

The ejection method is the same as that reported elsewhere (4), and involves mechanically and hydraulically-activated operation of the tool insert assembly to remove the filled part. For successful ejection, it has been found necessary to avoid macroscopic flashing during molding, and to apply ejection pressure evenly onto all of the PZT elements after molding. Thus, ejection is highly dependent on accurate dimensional tolerances in the tool inserts. In addition, tapering the PZT rods is known to facilitate ejection. As little as 0.5 to 1 degree taper has resulted in greatly eased part removal from the existing 1-3 composite mold (4). Figure 9 shows several PZT rods that fractured from the array during ejection and subsequent part handling during binder removal. These rods, which can be seen lying horizontally in the photograph, do not exhibit any taper along their length, and thus represent a worst-case scenario in terms of ejection behavior. Taper has been incorporated in the new design shown in Figure 7 to facilitate ejection of this configuration.

From measurements of the PZT rods in Figure 9, the length-to-diameter aspect ratio is seen to be more than adequate for any current 1-3 composite transducer application.

Conclusions and Recommendations

Except for the evaluation of lapped inserts and the square cross-section insert configuration, which are planned for completion within the coming weeks, Phase 1 of this program is complete. The program has met all of its original objectives, including: Demonstrating the basic tool insert materials concept, cost-effective insert fabrication approach, tool design and assembly, and tool operation under molding conditions. Many technical issues associated with tool insert tolerance control and positioning have been resolved through engineering changes. Such tool modifications are similar to those encountered during the development of the original 1-3 composite injection molding technology at MSI, and are to be expected as part of the tool debugging procedure. The difference in this program lies in the use of new tooling materials and mold configurations that are radically different than any employed in conventional plastics or ceramics injection molding. Given the pioneering nature of this work, it is a significant achievement that in only six months the tooling for 1-3 PZT composite preforms has been brought to the point of applications readiness.

The emphasis is now being placed on forming and evaluating 1-3 PZT/polymer composites of interest for Navy and commercial applications. MSI plans to accomplish this activity through Phase 2, as originally proposed. Phase 3 is expected to lead to an actual systems application.

Over the past months, MSI has identified and is pursuing several commercial applications for transducers operating in the same frequency ranges required by the US Navy for mine detection and classification and other littoral applications. These commercial applications are being developed with MSI IR&D funds and through customer purchase orders. In particular, there is a need for 1-3 composites operating in the 1 to 1.2 MHz frequency range for applications such as fish finding. MSI has supplied samples of 1-3 transducers made using the current mm-scale 1-3 technology. There is an urgent need for finer PZT elements in higher ceramic volume fractions to improve the resonance response of these composites. The tooling technology developed under Phase 1 and planned for refinement and application in Phases 2 and 3 would provide the necessary finer scale PZT 1-3 composite materials for this application.

Other private sector areas will benefit by the availability of low cost piezocomposite transducers for such applications as: Medical ultrasound, nondestructive evaluation, ocean surveying, industrial process control, and surveillance of submerged marine structures such as oil drilling platforms. MSI is continuing its ongoing business development activities with systems manufacturers in all of these areas. The new injection molding tooling method facilitates applications development and cost-effective small lot production runs for these systems, which has previously been a hindrance to near-term applications development.

In addition, MSI is the transducer materials manufacturing participant in a Technical Collaboration Program as part of Contract N00014-C-92-0212. This effort teams with participants from other NATO countries to pool resources in modelling, design, composite transducer fabrication, testing, and systems application. The objective is to refine and develop advanced 1-3 composite transducers for use in hydrophones, low frequency stacked arrays, and undersea imaging systems. The ability to build complex 1-3 transducers on a prototype and test basis is key to the success of this program. Phase 2 would provide the resources needed to refine the tooling approach and fabricate tooling for use in this effort.

In summary, MSI recommends that the present effort be transitioned into a Phase 2 program that concentrates on the following technical areas:

- 1) Refinement of the tooling to include: New mold insert materials, improved tool insert positioning methods, improved insert and cavity surface finish, and improved insert dimensional control.
- 2) Evaluation of the tooling, including determining the tool life through multiple operating cycles.
- 3) Pushing the limits of the tooling technology in terms of finer dimensions to make available higher frequency composite transducers for Navy and commercial applications.

- 4) Applying the tooling technology to make new 1-3 composite configurations, directed at specific Navy and commercial uses. Evaluate the transducers so generated in actual systems applications.

The Phase 2 effort will seek to improve piezoelectric composite device fabrication technology and performance by refining the composite PZT element shape and layout, produce sufficient materials to demonstrate device performance and process reproducibility, and demonstrate that the overall process cost is sufficiently low.

By properly interfacing the demonstrated tooling and composite prototyping method with appropriate composite design and testing, an optimum composite design for specific Navy and commercial applications can quickly be realized and demonstrated. For Phase 2, MSI proposes to expand the tooling development effort and work with design and applications specialists selected in conjunction with the ONR scientific officer to complete an iterative composite transducer design, fabrication and test program. The objective would be to establish transducer design parameters and fabricate demonstration transducers for specific Navy applications, such as undersea imaging and acoustic signature reduction. In Phase 3, the selected designs would be fabricated in larger quantities for use in a systems demonstration.

The new tooling technology will make available to the government a new generation of low cost piezoelectric ceramic/polymer composites tailored to perform in the frequency ranges of interest various undersea applications. MSI will seek to facilitate the implementation of this technology by providing transducers for evaluation by Navy facilities. Moreover, by working with Navy acoustic systems development contractors, MSI will integrate low cost transducer prototyping into design evolution for the development of improved acoustic systems.

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